PCT WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 7 : G01B 5/008, 7/008

A1

(11) International Publication Number: WO 00/14474

(43) International Publication Date: 16 March 2000 (16.03.00)

(21) International Application Number: PCT/US99/18968

(22) International Filing Date: 20 August 1999 (20.08.99)

(30) Priority Data:
09/149,192 8 September 1998 (08.09.98) US

(71) Applicant: BROWN & SHARPE MANUFACTURING COMPANY [US/US]; Precision Park, North Kingstown, RI 02852 (US).

(72) Inventor: CHARLTON, Thomas, Jr.; 120 Lantern Lane, North Kingstown, RI 02852 (US).

(74) Agent: MC CLELLAN, William, R.; Wolf, Greenfield & Sacks, P.C., 600 Atlantic Avenue, Boston, MA 02210 (US).

(81) Designated States: CA, JP, MX, European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

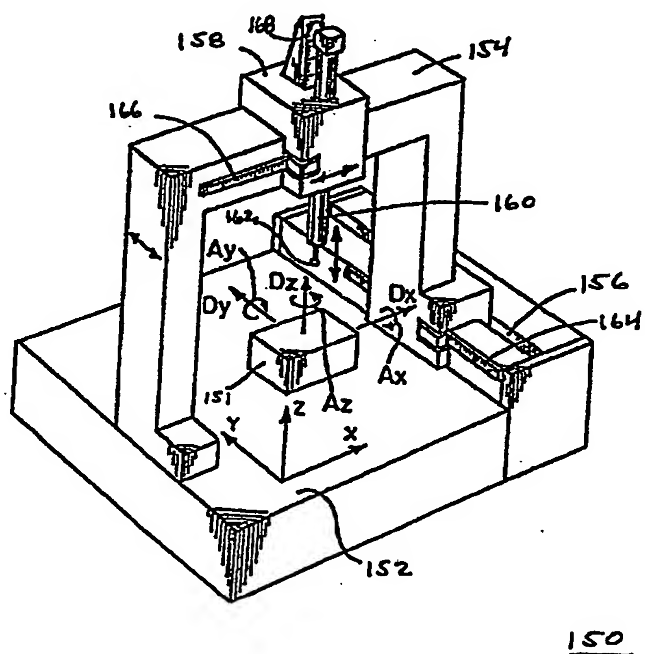
Published

With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: COORDINATE MEASURING MACHINE HAVING A MACHINE TOOL FRAME

(57) Abstract

A machine tool coordinate measuring machine (CMM). The CMM includes a frame having one or more members and a table on which the workpiece is secured. The members and table are movable relative to each other, typically along 3 axes. A probe assembly having a probe configured to contact a desired surface of the workpiece is mounted on one member of the machine tool frame and one or more scales are mounted on the machine tool frame to provide positional data identifying a relative position between various pairs of either the members and/or table along each axis. A controller controls the probe assembly, reads the scales to obtain the positional data. The controller includes a multidimensional temperature compensation unit that dynamically determines temperature characteristics of the machine tool frame based on information provided by temperature sensors mounted on the frame and compensates the positional data accordingly. A volumetric compensation unit mathematically models and measures repeatable geometric errors of the machine tool frame and compensates the positional data accordingly. Thus, the controller generates compensated positional data, which is stored and subsequently used by a conventional measurement planning, analysis and reporting unit. This unit is responsive to the operator, generating commands for use by the controller and analyzing the compensated positional data to determine the location of points along a surface of the workpiece. The machine tool CMM operates with high accuracy and repeatability in workshop environments and, as such, can be integrated into the workpiece manufacturing cycle to monitor in real time the quality of the process and to identify when corrective feed-back actions that prevent the production of defective components are required.



FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania	ES	Spain	LS	Lesotho	SI	Slovenia
AM	Armenia	FI	Finland	LT	Lithuania	SK	Slovakia
AT	Austria	FR	France	LU	Luxembourg	SN	Senegal
AU	Australia	GA	Gabon	LV	Latvia	SZ	Swaziland
AZ	Azerbaijan	GB	United Kingdom	MC	Monaco	TD	Chad
BA	Bosnia and Herzegovina	GE	Georgia	MD	Republic of Moldova	TG	Togo
BB	Barbados	GH	Ghana	MG	Madagascar	TJ	Tajikistan
BE	Belgium	GN	Guinea	MK	The former Yugoslav Republic of Macedonia	TM	Turkmenistan
BF	Burkina Faso	GR	Greece			TR	Turkey
BG	Bulgaria	HU	Hungary	ML	Mali	TT	Trinidad and Tobago
BJ	Benin	IE	Ireland	MN	Mongolia	UA	Ukraine
BR	Brazil	IL	Israel	MR	Mauritania	UG	Uganda
BY	Belarus	IS	Iceland	MW	Malawi	US	United States of America
CA	Canada	IT	Italy	MX	Mexico	UZ	Uzbekistan
CF	Central African Republic	JP	Japan	NE	Niger	VN	Viet Nam
CG	Congo	KE	Kenya	NL	Netherlands	YU	Yugoslavia
CH	Switzerland	KG	Kyrgyzstan	NO	Norway	ZW	Zimbabwe
CI	Côte d'Ivoire	KP	Democratic People's Republic of Korea	NZ	New Zealand		
CM	Cameroon			PL	Poland		
CN	China	KR	Republic of Korea	PT	Portugal		
CU	Cuba	KZ	Kazakstan	RO	Romania		
CZ	Czech Republic	LC	Saint Lucia	RU	Russian Federation		
DE	Germany	LI	Liechtenstein	SD	Sudan		
DK	Denmark	LK	Sri Lanka	SE	Sweden		
EE	Estonia	LR	Liberia	SG	Singapore		

COORDINATE MEASURING MACHINE HAVING A MACHINE TOOL FRAME

Background Of The Invention

Field of the Invention

The present invention relates generally to metrology and, more particularly, to coordinate measuring machines.

Related Art

Coordinate measuring machines (CMMs) have traditionally been used to gather dimensional data for inspection and process control purposes. For example, CMMs operating in three axes of movement are commonly utilized to process measurement and dimensional data to analyze trends in manufacturing processes and to provide data that can correct such processes before a workpiece or a workpiece feature drifts out of tolerance.

Typically, a workpiece is secured to a fixed table, and a measuring probe is secured to an arm which is movable in the vertical and horizontal planes. To measure the position of a point on the workpiece, the probe is brought into contact with the point and the X, Y and Z measuring scales of the CMM are read. To measure a distance between two points, the points are contacted successively, the coordinates of both points are read, and the distance is calculated from the coordinates. State of the art coordinate measuring machines have refinements such as high resolution measuring systems, electrical contact probes, motor drives, computer controlled drives and computer acquisition and data processing systems.

One example of a conventional moving bridge CMM is shown in Figure 1. Mounted on a fixed machine table 152 of CMM 150 is a workpiece 151 to be measured. The X-, Y- and Z- axes of CMM 150 are illustrated. In moving bridge CMM 150, a bridge 154 moves in one linear axis (the Y-axis) across the table on guideways 156 mounted on table 152. A carriage 158 travels perpendicular to the X-axis along bridge 154 (the Y-axis) on guideways mounted on bridge 154. Carriage 158 has a vertical control column or ram 160 that moves perpendicularly to the X- and Y-axes along the Z-axis. A probe assembly 162 mounted to the lower end of ram 160 moves vertically through bearings on carriage 158. As such, probe assembly 162 can be translated to any desired position within the measurement volume to measure points along a workpiece surface. A scale 164 between bridge 154 and table 152, a

scale 166 between carriage 158 and bridge 154, and a scale 168 between ram 160 and carriage 158 indicate the positions of the movable elements in the three axial directions. To measure the coordinates of a point on workpiece 151, probe 162 is brought into contact with the point of interest. Probe 162 senses contact and causes a system computer (not shown) to read and store the readings on the three scale systems. An example of a moving bridge coordinate measuring machine is the model MicroXcel 765 CMM manufactured by Brown & Sharpe Manufacturing Company, North Kingston, Rhode Island, USA.

Another conventional type of CMM, commonly referred to as a horizontal arm CMM is illustrated in Figure 2. Horizontal arm CMM 200 includes various components closed by a cover system, such as bellows 208, as is well known in the art. A horizontal arm assembly 206 is enclosed within bellows 208 at the front and a hard cover 210 at the rear. Horizontal arm CMM 200 includes a base 212 on which is supported a vertical column assembly 214 attached to an X- axis carriage movable along a first horizontal coordinate axis (the X-axis). Vertical column assembly 214 movably supports horizontal arm assembly 206, having mounted thereon a probe assembly 216. Horizontal arm assembly 206 is carried on the YZ carriage 218 movable vertically on vertical column assembly 214 along a second coordinate axis (the Z-axis). Horizontal arm assembly 206 is movable horizontally on a YZ carriage 218 along a third or Y-axis parallel to the longitudinal axis of horizontal arm 206. Each of the X-, Y- and Z-axes are orthogonal to each other in a manner well known in the art.

Base 212 supports a workpiece to be measured (not shown) which may be disposed within a measurement volume so as to be accessible for inspection by movement of probe assembly 216 to points of interest on the workpiece. Detachably mounted on base 212 and vertical column assembly 214 are pairs of spaced apart guideway members (not shown) each elongated and extending parallel to each other along the X-, Y- and Z-axes. Further features of horizontal CMM 200 are disclosed in U.S. Patent No. 4,887,360 to Hemmelgarn *et al.*, the specification of which is hereby incorporated by reference in its entirety. An example of a conventional horizontal arm coordinate measuring machine is the Layout Gauge 200H manufactured by Brown & Sharpe Manufacturing Company, North Kingston, Rhode Island, USA.

In operation the moving components of the CMM are supported on respective bearing surfaces that substantially minimize friction. The CMM is typically interfaced with a computer or similar information storage or processing device. As an operator moves the

probe in contact with the workpiece, the computer records the relative spatial position of the probe. This information is typically obtained by determining the position of the movable components of the CMM with respect to each of the machine's X, Y and Z bearing surfaces.

Typically, CMMs are located in inspection rooms adjacent to a workshop floor. As used herein, the term "workshop floor" refers to any production or manufacturing environment wherein workpieces or assemblies including one or more workpieces are manufactured. Such term is meant to encompass those environments not suitable for the performance of traditional dimensional metrology processes due to the errors induced in the measurements by the environment. Once a workpiece is machined, it is transported to an inspection room for dimensional verification. The workpiece is then measured, typically using a conventional cartesian CMM such as a horizontal arm or moving bridge CMM. Typically, a myriad of measurement points on the workpiece surface are recorded and analyzed to insure the workpiece has been manufactured in tolerance.

There is a need to locate the CMMs as close as possible to the workshop floor where the workpieces are manufactured to reduce the time associated with such verification processes. The closer the CMM is to the production site for the workpieces and assemblies, the more streamlined and efficient the manufacturing process. Typically, the machine tools or other equipment used to manufacture the workpiece remain idle during dimensional verification. Reducing such time, therefore, increases the unit production time. There are also costs associated with the creation and maintenance of the proper inspection room environment. Systems included in the creation of such an environment include those that prevent penetration of dust into the inspection room, eliminate or compensation for workshop floor vibrations, control temperature, etc., as is known in the art.

One conventional approach has been to reduce the size or otherwise configure the inspection rooms so as to enable the placement of the CMM near the production line. However, the cost of a CMM is significant. As such, most manufacturers cannot populate a production floor with the requisite or desired number of CMMs to measure a workpiece immediately after a manufacturing process is completed. Thus, the majority of workpieces must still be transported to another location to be measured.

Furthermore, placement of CMMs on the workshop floor have met with limited success due to the harsh environment typically existing at such locations. Such an environment that has not been successively guarded against in conventional systems. For

example, the CMM may be subject to extremely large temperature variations, spatial temperature gradients and temporal temperature gradients, depending where on the workshop floor the CMM is located. Other environmental effects that have not been successively prevented from adversely affecting the accuracy or reliability of the CMM include vibration, airborne particles and the like, as is well known in the art.

As a result, attempts have been made to create a ruggedized CMM immune to the workshop floor environment. One conventional approach has been to incorporate CMMs in a machine tool frame suitable for use in such a harsh environment. As noted, the workshop environment often includes machine tools for manufacturing all or part of a workpiece. Some machine tools have been around for generations while others are just becoming available. However, in all cases, these machines, including their frames, have been proven to be incapable of withstanding the harsh workshop floor environment. Unfortunately, the incorporation of CMM components into a machine tool frame has met with limited success. In particular, these machines have limited measurement accuracy and reliability due their being unable to compensate for the various environmental conditions noted above.

What is needed, therefore, is a cost effective and reliable CMM for use in a workshop floor environment capable of successively operating in a production environment. Such a system should be capable or providing the requisite degree of accuracy despite the local environment.

Summary of the Invention

The present invention is a machine tool coordinate measuring machine (CMM) and method for using the same to measure a workpiece in a workshop environment that overcomes the above and other drawbacks of conventional CMMs designed for use in workshop environments. The machine tool CMM includes a machine tool frame having one or more members and a table on which the workpiece is secured. The members and table are movable relative to each other along at least one, and preferably three, axes. A probe assembly having a probe configured to contact a desired surface of the workpiece is mounted on one member of the machine tool frame and one or more scales are mounted on the machine tool frame to provide positional data identifying a relative position between pairs of the members and/or table along the at least one axis. A scanning controller configured to control the probe assembly and to receive scale and probe feedback information to obtain the positional data is also included. The scanning controller includes a multidimensional temperature compensation unit that dynamically determines temperature characteristics of the machine tool CMM based on information provided by temperature sensors mounted on the frame, and compensates the positional data obtained from the scales accordingly. A volumetric compensation unit configured to mathematically model and measure repeatable geometric errors of the machine tool frame and to compensate the positional data accordingly is also included. Preferably, a deflection compensation unit is also included to measure mechanical deflections of the machine tool frame based on signals generated by deflection sensors located on the machine tool frame. Thus, the scanning controller receives positional data from the scales and compensates for errors in such positional data due to the machine tool frame and the workshop floor environment in which it is located. The compensated positional data is subsequently used by a measurement planning, analysis and reporting unit that is responsive to the operator, controls the CMM and analyzes the compensated positional data to determine the location of points along a surface of the workpiece.

Significantly, the incorporation of these compensation units in a CMM implemented on a machine tool frame enables the machine tool CMM of the present invention to operate with high accuracy and repeatability in workshop environments. As a result, the machine tool CMM can be integrated in to the workpiece manufacturing cycle to monitor in real time the quality of the manufacturing.

Another advantage of the present invention is that the mechanical bearings of the machine tool frame are utilized to provide machine movement, eliminating the use of pneumatic-based systems typically used in CMMs. This provides increased accuracy and reliability in the workshop environment, to external mechanical vibrations.

The use of a well known machine tool frame suitable for the anticipated workshop environment, in combination with other features of the present invention, has many advantages. The use of a machine tool frame enables the additional use of the electronics associated with the operation of the machine tool frame, typically provided by the machine tool manufacturer, provides for a machine tool CMM that has a high maintenance component familiarity. It also provides for increased reliability and operational time as compared to other CMMs placed in a workshop environment since the machine tools for which the frame was designed are capable of being implemented in such harsh environments without experiencing significant adverse effects. A still further advantage is that the resulting machine tool CMM is cost effective due to the use of a commonly available machine tool frame.

Another advantage of the present invention is that the CMM is insensitive to temperature variations, spatial temperature gradients and temporal temperature gradients, making the machine tool CMM, in combination with other features of the present invention, capable of accurately operating in a workshop environment.

Thus, the use of certain embodiments of the machine tool CMM of the present invention eliminates the time traditionally associated with transporting parts from the workshop floor to the inspection room, reduces the manufacturing line down time associated with waiting for the workpieces to be dimensionally verified, and eliminates the costs associated with the construction and maintenance of environmentally controlled inspection rooms.

Further features and advantages of the present invention as well as the structure and operation of various embodiments of the present invention are described in detail below with reference to the accompanying drawings.

Brief Description of the Drawings

The present invention is pointed out with particularly in the appended claims. The above and other advantages of this invention may be better understood by referring to the following description when taken in conjunction with the accompanying drawings in which

similar reference numerals indicate like or functionally similar elements or method steps. Additionally, the left-most one or two digits of a reference numeral identify the figure in which the reference numeral first appear.

Figure 1 is a perspective view of a conventional moving bridge coordinate measuring machine (CMM).

Figure 2 is a perspective view of a conventional horizontal arm CMM.

Figure 3 is a front perspective view of an exemplary machine tool frame suitable for use in the machine tool coordinate measuring machine (CMM) of the present invention.

Figure 4 is a rear perspective view of an exemplary machine tool frame suitable for use in the machine tool CMM of the present invention.

Figure 5 is a system block diagram of one embodiment of the machine tool CMM of the present invention.

Detailed Description

The present invention is a coordinate measuring machine (CMM) for use in workshop floor environment that overcomes the above and other drawbacks of conventional CMMs. The CMM of the present invention, referred to herein as a machine tool CMM, includes a basic frame and electronics of a machine tool and several advanced CMM control and data processing elements to form a machine tool CMM capable of reliably providing accurate dimensional measurements in a production floor or other manufacturing environment typically unsuitable for performing dimensional verification, referred to herein as a workshop floor environment.

Figure 3 is a front perspective view of a machine tool frame suitable for use in the present invention. Figure 4 is a rear perspective view of the machine tool frame illustrated in Figure 3. Rugged machine tool frames are well-known throughout the manufacturing industry. Exemplary machine tool frames suitable for use in the present invention are provided by companies such as Bridgeport Milling Machine, Bridgeport, CT, Cincinnati-Milacron, Cincinnati, OH, Monarch Machine Tool, Cortland, NY, Giddings and Lewis, Fond du Lau, WI, Ingersoll Milling, Rockford, IL and many others. The exemplary machine tool frame illustrated in Figures 3 and 4 is a machine tool frame used in a Torq-Cut, model 30 machine tool available from Bridgeport Milling Machine, Bridgeport, CT. The relatively high production volumes and demands imposed by manufacturing conditions make

machine tool frames cost effective solutions for providing a rugged, reliable platform for operating a CMM to perform dimensional metrology in a workshop environment.

The exemplary machine tool frame 300 is a knee-type (or C-section) machine tool frame that includes a plurality of members or elements and a table on which a workpiece is secured. The table is movable relative to the machine tool frame along the X-, Y- and Z-axes. This C-section machine tool frame 300 includes a horizontal base 302 on which a vertical column assembly 304 is fixedly mounted. A tool arm 306 is fixed to and extends horizontally from vertical column assembly 304 over base 302. Base 302 supports a carriage 308 mounted on parallel rails or guideways 310 that enables carriage 308 to travel toward and away from vertical column 304 along the Y-axis under the control of a drive motor 307 (obscured from view under carriage 308). Table 314 is mounted to a second carriage 313 that moves across carriage 308 on guideways 312 in another linear axis (the X-axis) perpendicular to the Y-axis. A drive motor 315 controls the position of carriage 313. Collectively, these carriage assemblies are commonly known as a cross-slide assembly.

A workpiece (not shown) to be measured is secured to table 314 for contact by a probe assembly 317 installed at the lower end of a vertical control column or ram 318 movably mounted on horizontal tool arm 306. A drive motor 319 controls the position of ram 318 perpendicularly to the X- and Y-axes along the Z-axis. Probe assembly 317 is mounted in a conventional manner on ram 318 and can be translated to any desired position within a measurement volume to measure points along a workpiece surface. A scale 322 between base 302 and carriage 308, a scale 320 between carriage 308 and carriage 313, and a scale 324 between ram 318 and tool arm 306 indicate the positions of the movable elements in the three axial directions. A number of temperature sensing elements 301 are incorporated at predetermined locations on the machine tool frame structure to provide data for temperature compensation algorithms performed by a temperature compensation unit described below. Also, in certain embodiments, mechanical deflection sensors 303 are also mounted in the machine tool frame for sensing mechanical deflections.

A block diagram of one embodiment of the machine tool CMM of the present invention is illustrated in Figure 5. Machine tool CMM 500 includes machine tool frame 300 described above with reference to Figures 3 and 4, as well as a number of CMM control and data processing elements 502 for obtaining and processing positional information to determine the location of points on a workpiece surface. In the embodiment shown in Figure 5, machine

tool frame 300 has mounted thereon a scale system 522 for providing indications of the relative position of probe assembly 317 and the workpiece secured to the table 314 along each of the axes. In the illustrative embodiment, scale system 522 includes scales 320, 322 and 324. Drive motors 524 translate each of the movable machine tool frame members, each driven by a servo amplifier 523. In the illustrative embodiment, drive motors 524 include motors 315, 319 and 307, as shown in Figures 3 and 4, to translate the table 314 along the X- and Y-axes and the probe assembly along the Z-axes. As noted, temperature sensors 301 and probing system 317 are located on machine tool frame 300 and, as such, are shown schematically in Figure 5.

CMM elements 502 include a scanning controller 504 that operates with scale system 522, drive motors 524, temperature sensors 301 and probing system 317 on machine tool frame 300, directing probe assembly 317 and processing positional information as described below. As one skilled in the relevant art would find apparent, scanning controller 504 includes other electronics, software, firmware and the like to operate with elements on the machine tool frame 300 and the control computer 506. . These well known systems are not pertinent to the present invention and, as such, are not described herein. The scales 522, drive motors 524, temperature sensors 301 and probing system 317 are connected to control computer 506, generally through input/output electronics connected to a backplane of scanning controller 504, as is well known in the art.

Control computer 506, which in the illustrative embodiment is implemented on any conventional computer platform, is responsive to a measurement planning, analysis and reporting unit 512 residing in a host computer 511. Planning, analysis and reporting unit 512 receives operator inputs indicating the type of measurement to be made, analysis to be performed, or report to be generated. Unit 512 generates commands to control computer 506 to implement such operator requests and provide results of such operations. The measurement planning, analysis and reporting unit 512 may be any such processing system now or later developed that includes workpiece geometry processing software. Such software provides programming facilities, trajectory control processes and data analysis capability to perform data collection and reduction operations. Such processes are considered to be well known in the art and are commercially available. For example, exemplary systems suitable for use in the present invention include PC-DMIS available from Wilcox Associates, Inc, California, and SCEPTRE available from Electronic Measuring Devices, Flanders, NJ. Such systems are

commonly used in conjunction with moving bridge CMMs such as the MicroXcel 765 CMM available from Brown & Sharpe Manufacturing Co., North Kingstown, Rhode Island, USA.

In a preferred embodiment of the present invention, probe assembly 508 includes an analog probe, and scanning controller 504 includes well known processing features for controlling the movement of the analog probe. In this embodiment, scanning controller 504 receives and processes feedback signals from probe system 317 and scales 522 indicative of the relative position of the analog probe to the workpiece surface. Probe assembly 317 and scanning controller 504 utilize well-known closed loop scanning techniques as is known in the art to enable the scanning controller 504 to generate servo control signals to drive probe assembly 317 to cause the analog probe to follow the workpiece surface.

The use of such servo-feedback controller techniques is preferred to verify the dimensions of equipment and devices having unknown or partially known contoured, free-form surfaces and complex part geometries. Such systems provide higher data densities and better accuracies than other probing techniques. This enables the machine tool CMM 500 to provide the necessary degree of control over the manufacturing process to insure that the workpiece dimensions are consistently within tolerances. Suitable scanning controller 504 and analog probe assemblies are commonly available from Brown & Sharpe Manufacturing Company, North Kingston, Rhode Island, USA, Zeiss, Oberkochen, Germany, Electronic Measuring Devices (EMD), Flanders, NJ, Starrett, Mt. Airy, NC and others.

It should be understood that in alternative embodiments, probe assembly 508 may include other types of probes, as is well known in the art. For example, in one particular embodiment probe assembly 317 includes a touch trigger probe. Such an embodiment may be implemented in production environments where workpieces having traditional geometrically-shaped or prismatic shapes are manufactured.

Controller 506 includes a temperature compensation unit 514, a volumetric compensation unit 516 and, preferably, a deflection compensation unit 518. Controller 506 is configured to control probe system 317 and to read scales 522 to obtain positional data representative of points on a workpiece surface, and to compensate for errors in the positional data due to the workshop environment in which CMM 500 is implemented. The geometric or multidimensional temperature compensation unit 514 dynamically determines temperature characteristics of machine tool frame 300 and the workpiece based on information provided by temperature sensors 301 mounted thereon, and compensates the positional data obtained

from the scale system 522 accordingly. The temperature compensation unit 514 is described in further detail below.

Volumetric compensation unit 516 is configured to mathematically model and measure repeatable geometric errors of the machine tool frame 500 and to compensate the positional data accordingly. Volumetric compensation unit 516 implements well-known methodologies to mathematically model repeatable geometric errors of machine tool CMM 500. Such techniques have been commonly used to perform similar compensation in positioning machines such as CMMs, machine tools and robots.

Volumetric compensation unit 516 removes these errors from the positional data provided by scales 522 during use of machine 500 by applying mathematical model equations. This improves the accuracy of the machine 500 in its intended function as a workshop floor machine tool CMM. The techniques implemented in volumetric compensation unit 516 are well known techniques commonly used in the metrology industry. In one preferred embodiment, the volumetric compensation unit 506 utilizes processes and apparatus disclosed in commonly owned U.S. Patent Nos. 4,939,678 and 4,884,889 to Beckwith et al., and U.S. Patent Application 08/523,014 entitled "CALIBRATION SYSTEM FOR COORDINATE MEASURING MACHINE", filed September 1, 1995 and naming as inventor Paul J. Anderson, the disclosures of which are hereby incorporated by reference in their entireties.

As one skilled in the art would find apparent, volumetric compensation techniques such as those noted above must be calibrated for the type and configuration of the machine tool frame, depending on the technique implemented. Generally, during machine construction and adjustment, volumetric compensation unit 516 performs measurements for establishing the mathematical models for the particular machine tool frame. Using auxiliary metrology equipment at the final assembly stage or during re-adjustment at a customer's facility, the systematic kinematic errors of each axis are carefully measured as a function of the machine's scale reading for the axis under test. There are typically six such errors per axis. The results of these measurements are typically stored on a disk in control computer 506 or, alternatively, in the host computer 511. During use, the actual scale readings are used to "look up" the previously measured errors at the indicated location, and subtract their effects from the scale readings to produce a more accurate set of values for the probe location. It should also be understood that the data obtained for use by volumetric compensation unit 516 be formatted in

a format appropriate for the implemented algorithms. Such data acquisition and formatting is considered to be well known in the art.

As shown in the exemplary machine tool frame 300 illustrated in Figures 3 and 4, cross-slide assembly extends from the knee portion of the C-section frame. This configuration is subject to significant potential mechanical deflections of the structure due to gravitational forces acting on the machine elements and/or workpiece placed on the machine table, causing errors in the workpiece measurements.

Accordingly, in accordance with a preferred embodiment of the present invention, a deflection compensation unit 518 is included in the control computer 506. Generally, such a deflection compensation unit 518 includes one or more additional sensors 303 in machine structure 300 to sense the mechanical deflections experienced by frame 300. In one embodiment, deflection sensors 303 include strain gage sensors, although other sensor types may be used to accomplish the same purpose. The deflection control unit 518 detects such deflections and implements well known deflection algorithms for measuring the deflections and using such information to provide compensation to the positional information obtained from scale system 522. It should be apparent that for each machine tool structure, optimization is required to establish the sensitivity of the structure to gravitational deflection, and to find the best location for the placement of sensors 303.

In one embodiment, deflection compensation unit 518 is integrated into volumetric compensation unit 516, as illustrated by dashed box 517. In the illustrative embodiment shown in Figure 5, deflection compensation unit 518 is implemented as a stand-alone process implemented as a software module or modules in control computer 506.

Of the conditions on the workshop floor that affect CMM accuracy, temperature has the greatest effect. Any temperature change in a room where the CMM is located distorts the geometry of both the machine structure and the workpiece, and eventually increases dimensional measurement uncertainty during inspection. The goal of any CMM operation is to eliminate thermally-induced errors in measuring performance. Thus, temperature compensation for the expansion and distortion of the machine structure is an essential element for accurate shop floor measurement, particularly since dimensions must be referenced to 20C, in accordance with International Organization for Standardization (ISO) standard ISO-1, and machine distortion leads to geometric errors not detectable by volumetric compensation unit 516. In a preferred embodiment, multidimensional or geometric temperature

compensation techniques are implemented to provide full three-dimensional compensation for temperature variations, across the machine frame 500, as well as spatial and temporal temperature gradients.

The first-order and most widely used correction techniques apply equation (1) to each of the machine axes, and, usually, the workpiece.

(1) del-L = a*L*(T-20)

where, del-L is the change in length due to temperature; a is the coefficient of expansion; L is the length at 20 C; and T is the actual temperature.

Applying this equation to each of the axes of machine 500 and the workpiece is frequently called "linear temperature compensation" and is known to be used for CMMs manufactured by Brown & Sharpe Manufacturing Company, Zeiss, Sheffield, etc. The coefficient of expansion (a) is a generally available material property. Preferably, this value is adjusted slightly to optimize measurement accuracy on the specific machine tool frame 500, as is well known in the art.

However, it is preferable that a more advanced approach, commonly referred to as "geometric temperature compensation" is utilized. Geometric or multidimensional temperature compensation takes into account the distortions of machine frame 500 due to temperature differences within the machine. This may involve bending of a single machine member or element, and/or rotations of individual machine members relative to each other, or to the workpiece.

Related to the widely used volumetric compensation techniques briefly described above, "linear temperature compensation" may be said to adjust the axial displacement errors for temperature, while the "geometric temperature compensation" may be said to adjust the transverse displacement errors (straightness), angular errors (yaw, pitch, roll) and orthogonality errors (squareness) for the effects of temperature.

A common representations of single element bending is shown in Equation (2):

(2) del-L = c*x^2*(T2-T1) for a straightness, and

where del-L is a transverse error; c is a proportionality constant; x is a position along the bending element; and T1, T2 are temperatures measured at two separated locations on the element.

Optimization in the application of Equation (2) is required through determination of the proportionality constant and the selection of the two temperature measurement locations. For the simplest relative rotation of an element, a linear approximation is used, as follows, although higher order terms (quadratic, cubic, etc.) are also possible.

(3) $$\text{del-angle} = d*x*(T4-T3)$$

where del-angle is a temperature dependent rotation angle; d is a proportionality constant; x is a position along the rotating element; T3, T4 are temperatures measured at two separated locations on one element or at different locations on two elements of the machine structure. Again, optimization in the application of Equation (3) is required through determination of the proportionality constant and the selection of the two temperature measurement locations.

Changes in orthogonality, or squareness, can be handled simply by

(4) $$\text{del-angle} = e*(T6-T5)$$

where del-angle is the change in orthogonality; e is a proportionality constant; T5, T6 are temperatures measured at two separated locations on one element or at different locations on two elements of the machine structure. Again, optimization in the application of this equation is required through determination of the proportionality constant and the selection of the two temperature measurement locations. Application of such geometric temperature compensation are commonly used on CMMs manufactured by Brown & Sharpe Manufacturing Company and Zeiss and on a laboratory machine tool by NIST and others.

Such a temperature compensation system is capable of identifying and calculating temperature gradients and transients. The system includes the strategic placement of sensors 301, which is a function of the type and configuration of the machine tool frame, the individual machine, and the anticipated operating environment, preferably determined empirically at system installation. In one embodiment, the temperature compensation unit is capable of providing temperature compensation techniques for an operating temperature range

of 15-40C, making CMM 500 relatively insensitive to temperature variations, spatial temperature gradients and temporal temperature gradients.

While various embodiments of the present invention have been described above, it should be understood that they have been presented by way of example only, and not limitation. Thus, the breadth and the scope of the present invention are not limited by any of the above exemplary embodiments, but are defined only in accordance with the following claims and their equivalents.

CLAIMS

1. A CMM for measuring a workpiece in a workshop environment comprising:

a machine tool frame having one or more elements and a table on which the workpiece is secured, said one or more elements and said table movable relative to each other along at least one axis;

a probe assembly mounted on said machine tool frame having a probe configured to contact a desired surface of the workpiece;

one or more scales each mounted on said machine tool frame to provide positional data identifying a relative position between two of said at least one movable element and said table along one of said at least one axis;

a scanning controller configured to control said probe assembly and to read said one or more scales to obtain said positional data, said controller including:

a multidimensional temperature compensation unit configured to dynamically determine one or more temperature characteristics of said machine tool frame based on information provided by a plurality of temperature sensors mounted on said machine tool frame, said temperature compensation unit further configured to compensate said positional data accordingly, and

a volumetric compensation unit configured to mathematically model and measure repeatable geometric errors of said machine tool frame configuration and to compensate said positional data accordingly; and

a measurement planning, analysis and reporting unit, responsive to user inputs, configured to control said scanning controller and to analyze said compensated positional data representing measurement points along a surface of the workpiece.

2. The CMM of claim 1,

wherein the probe assembly includes an analog probe, and

wherein said scanning controller further comprises means for providing servo control signals to said analog probe.

3. The CMM of claim 1, wherein said probe assembly includes a touch trigger probe.

4. The CMM of claim 1, wherein said multidimensional temperature compensation unit dynamically determines temperature characteristics of the workpiece

5. The CMM of claim 1, wherein said temperature characteristics include temperature variations and spatial and temporal temperature gradients.

6. The CMM of claim 1, further comprising one or more deflection sensors mounted on said machine tool frame, and wherein said scanning controller further comprises deflection compensation means for compensating said positional data obtained from said scales for mechanical deflections in said machine tool frame.

7. A CMM for measuring a workpiece in a workshop environment comprising:

a machine tool frame having one or more elements and a table on which the workpiece is secured, said one or more elements and said table movable relative to each other along at least one axis;

a probe assembly mounted on said machine tool frame having a probe configured to contact a desired surface of the workpiece;

one or more scales each mounted on said machine tool frame to provide positional data identifying a relative position between two of said at least one movable element and said table along one of said at least one axis;

a scanning controller configured to control said probe assembly and to read said one or more scales to obtain said positional data, said controller including:

temperature compensation means for compensating said positional data obtained from said one or more scales for temperature variations and spatial and temporal temperature gradients of said machine tool frame and the workpiece, including a plurality of temperature sensors mounted on said machine tool frame,

volumetric compensation means for compensating said positional data obtained from said one or more scales for repeatable geometric errors of said machine tool frame, and

deflection compensation means for compensating said positional data obtained from said scales for mechanical deflections in said machine tool frame; and

measurement planning, analysis and reporting means for performing workpiece geometry processing including data collection and reduction means for collecting and processing said compensated positional data.

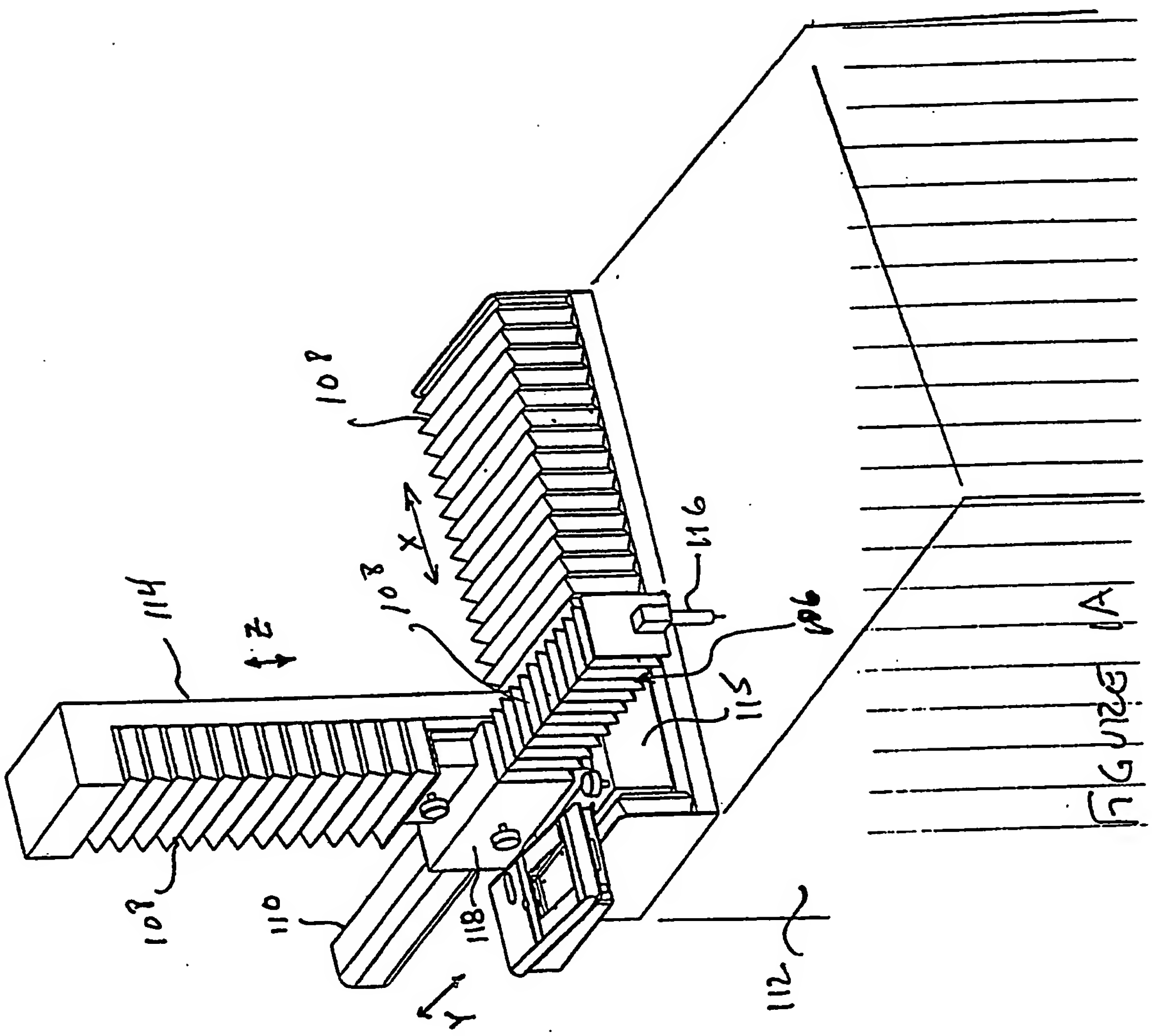


FIGURE 1A

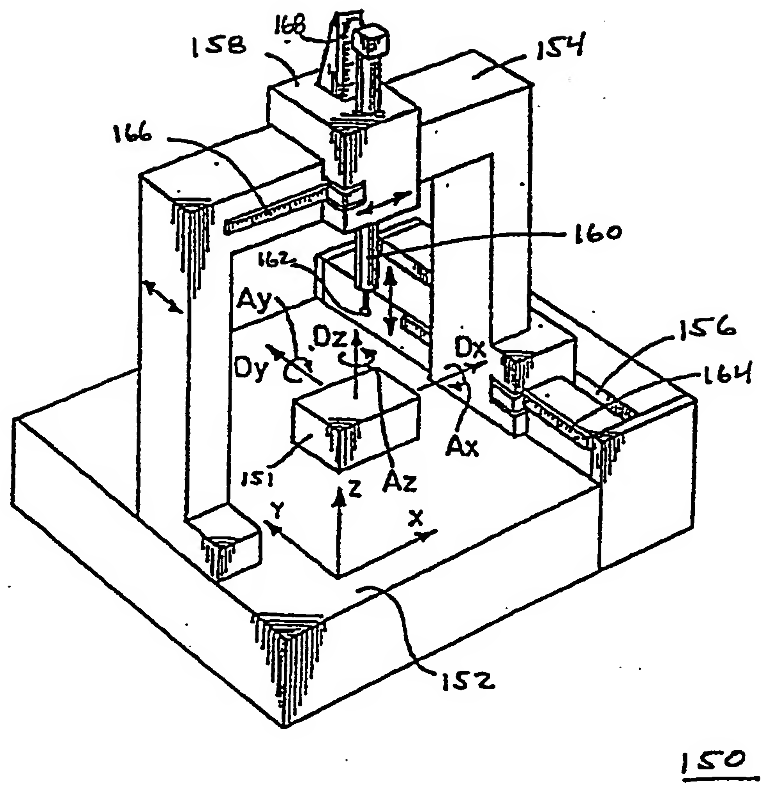


FIGURE 1B

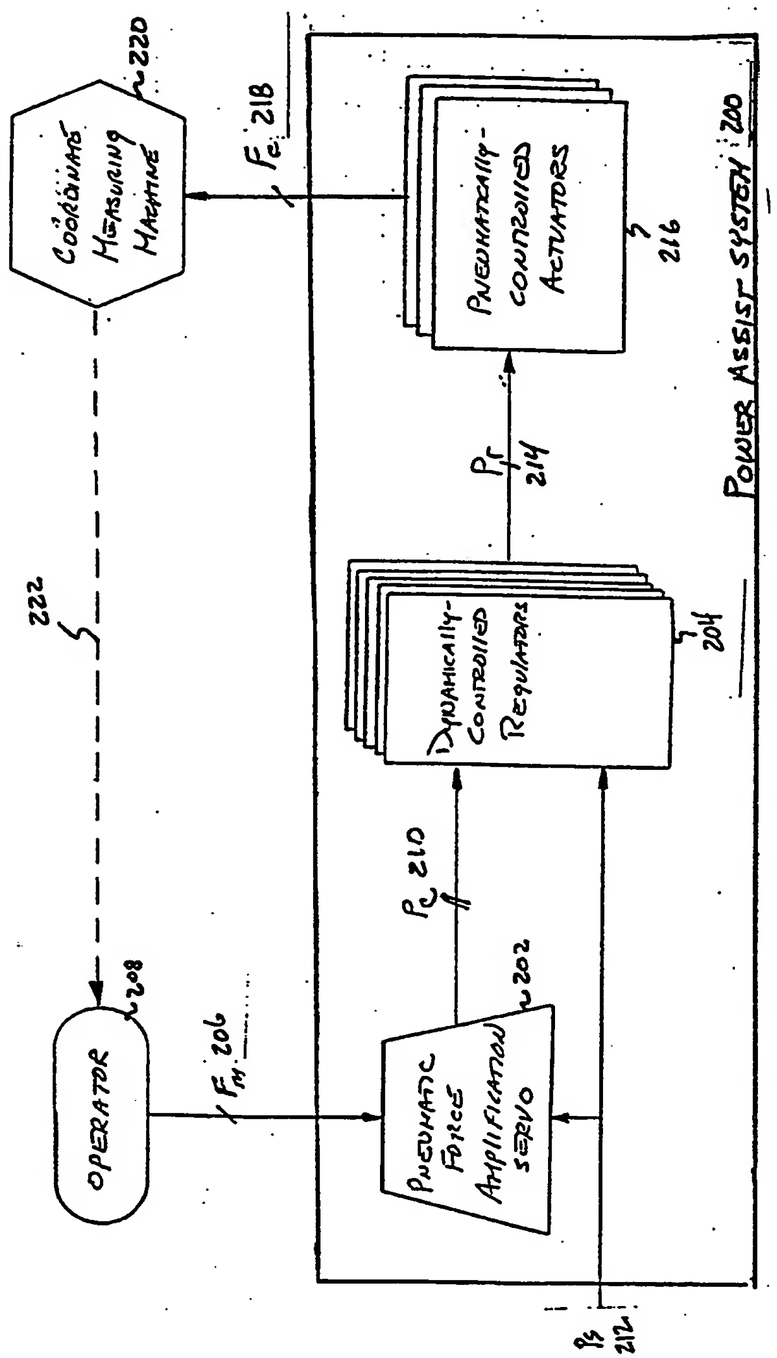

COORDINATE MEASURING MACHINE
220
F_c 218
PNEUMATICALLY-CONTROLLED ACTUATORS
216
POWER ASSIST SYSTEM 200
P_r 214
DYNAMICALLY-CONTROLLED REGULATORS
204
222
P_c 210
OPERATOR
208
F_m 206
PNEUMATIC FORCE AMPLIFICATION SERVO
202
P_s 212

FIGURE 2A

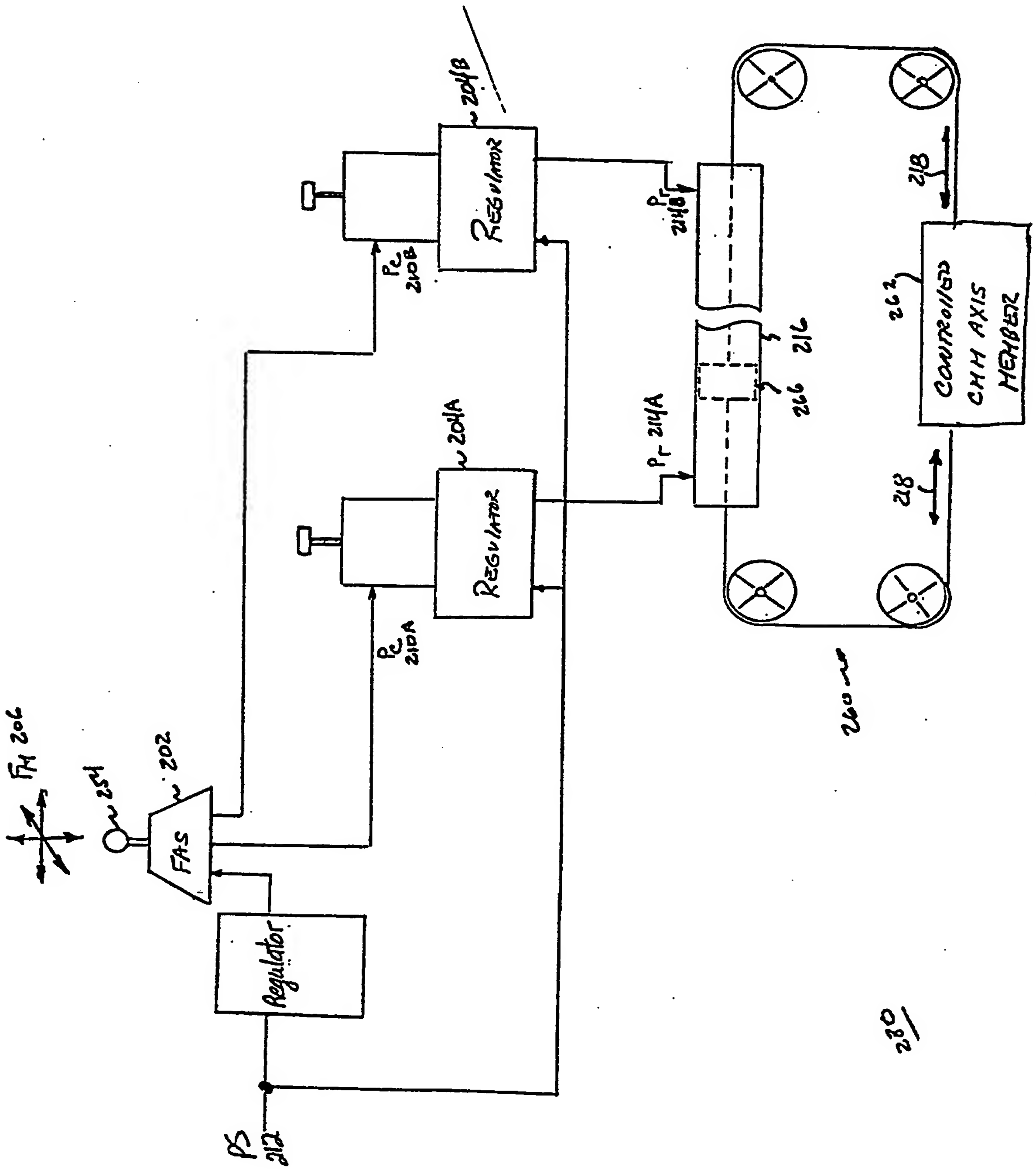

FH 206
254
202
FAS
Regulator
PS
212
Pc
210A
Pc
210B
Regulator
204A
Regulator
204B
Pr 214A
Pr
214B
216
266
218
218
262
CONTROLLED
CMM AXIS
MEMBER
260
280

FIGURE 2B

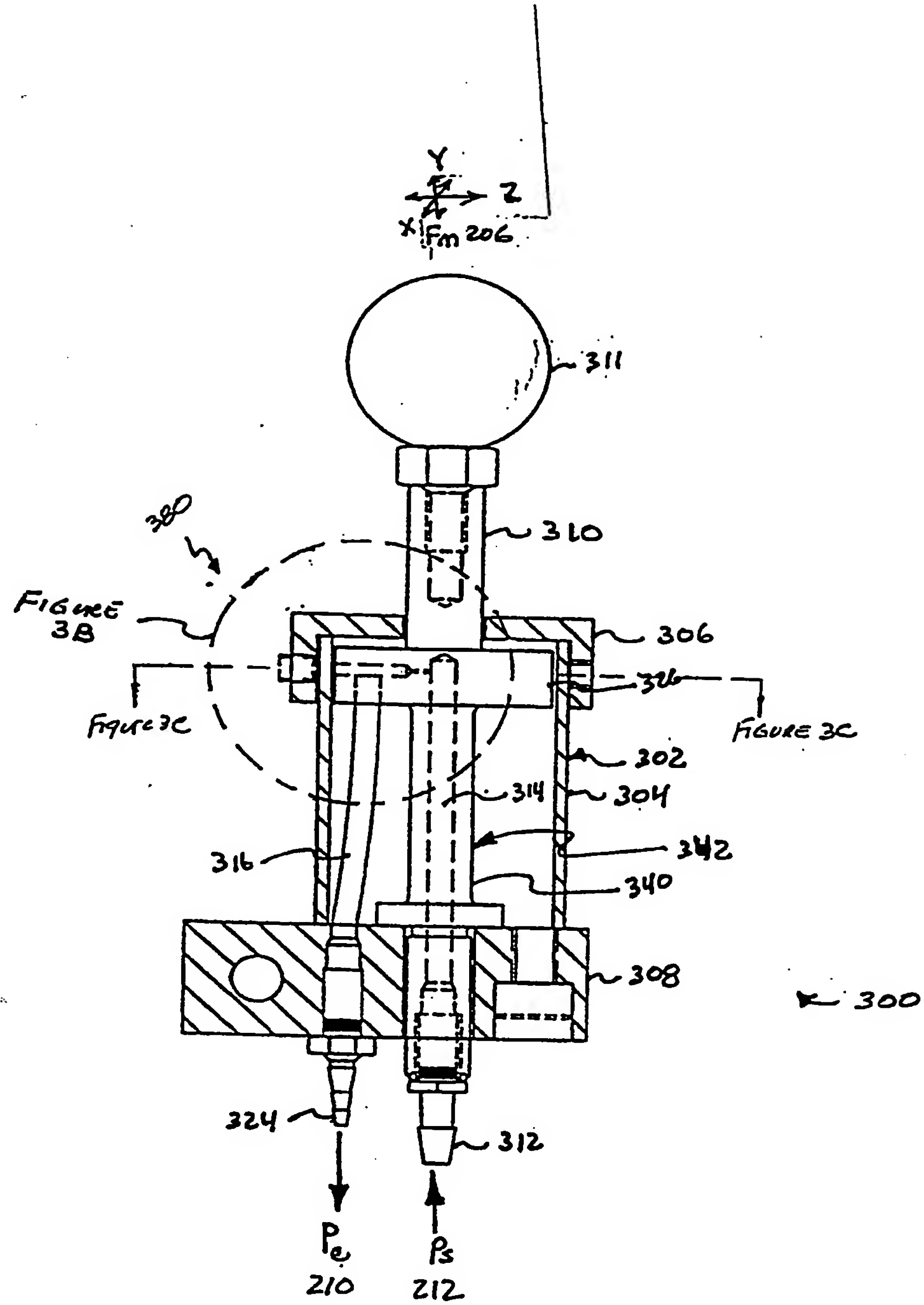
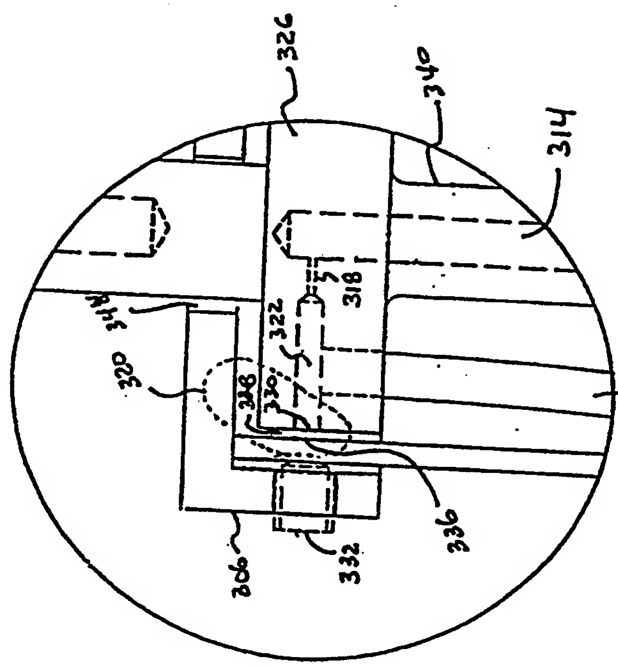

Y
Z
X
Fm 206
311
310
380
FIGURE 3B
306
Figure 3C
FIGURE 3C
326
302
304
314
316
342
340
308
300
324
312
P_e
210
P_s
212

FIGURE 3A



380

FIGURE 3B

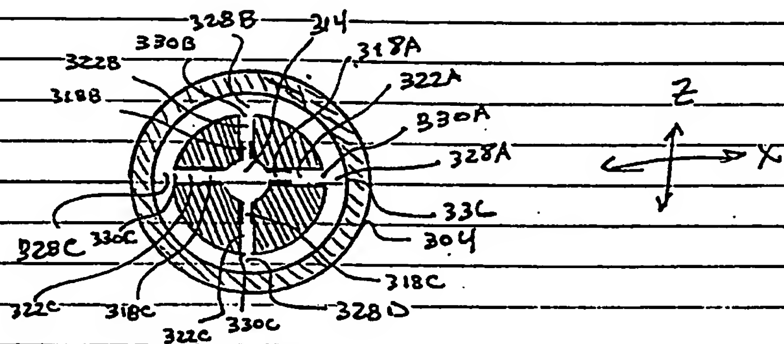

328B
314
330B
318A
322B
322A
318B
330A
328A
336
304
328C
330C
318C
322C
318C
328D
322C
330C
Z
X

Figure 3C

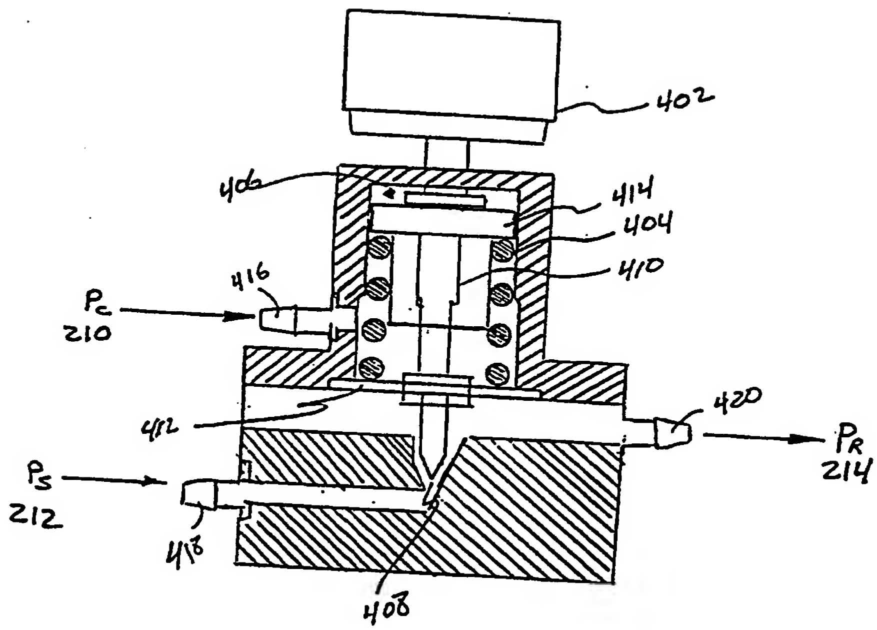


FIGURE 4

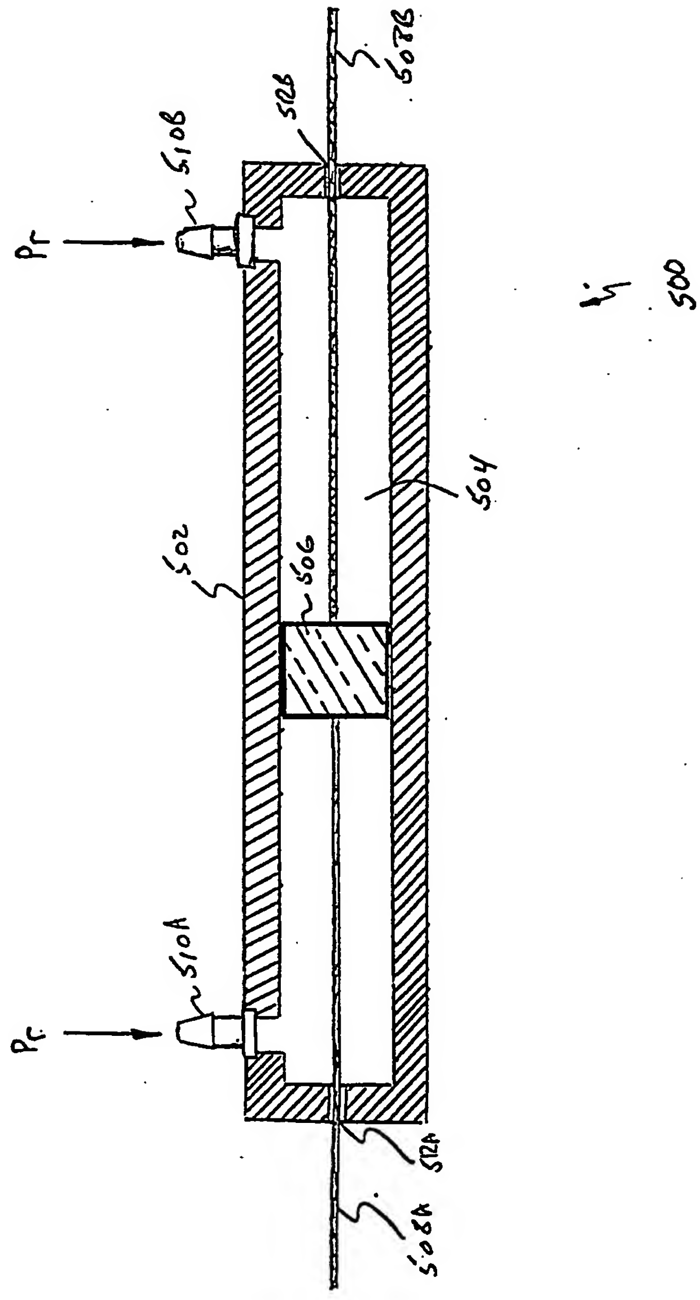


FIGURE 5

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 99/18968

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G01B5/008 G01B7/008

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G01B B23Q

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 97 43703 A (AUTOMATED PRECISION INC ;LAU HERBERT (US); LAU KAM C (US); MA QUAN) 20 November 1997 (1997-11-20) page 8 -page 26	1
Y	US 5 412 880 A (RAAB SIMON) 9 May 1995 (1995-05-09) column 2 -column 3; claims 1-20	1
Y	WO 97 46925 A (BOEING CO ;GREENWOOD THOMAS A (US); PASTUSAK THOMAS W (US)) 11 December 1997 (1997-12-11) claims 1-34	7
Y	EP 0 519 638 A (RENISHAW METROLOGY LTD) 23 December 1992 (1992-12-23) column 4 -column 15	7

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier document but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
17 December 1999	11/01/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Dietrich, A

1

Form PCT/ISA/210 (second sheet) (July 1992)

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	US 4 547 847 A (OLIG EUGENE A ET AL) 15 October 1985 (1985-10-15) column 7 -column 30	1-7
A	EP 0 740 982 A (FARO TECH INC) 6 November 1996 (1996-11-06) column 6 -column 17	1-7
A	US 4 782 598 A (GUARINI ANTONIO) 8 November 1988 (1988-11-08) column 5 -column 15	1,7
A	US 4 939 678 A (BECKWITH JR WALTER L) 3 July 1990 (1990-07-03) cited in the application claims 1-11	1,7

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/US 99/18968

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 9743703 A	20-11-1997	NONE	
US 5412880 A	09-05-1995	US 5402582 A	04-04-1995
		CA 2110927 A	24-08-1994
		DE 4403901 A	25-08-1994
		DE 9421789 U	29-08-1996
		DE 9421790 U	29-08-1996
		DE 9421791 U	29-08-1996
		DE 9422039 U	25-09-1997
		DE 9422040 U	09-10-1997
		DE 9422041 U	09-10-1997
		DE 9422042 U	09-10-1997
		DE 9422043 U	09-10-1997
		FR 2702043 A	02-09-1994
		GB 2275339 A,B	24-08-1994
		IT MI940285 A	23-08-1994
		JP 7004950 A	10-01-1995
		US 5408754 A	25-04-1995
		US 5611147 A	18-03-1997
WO 9746925 A	11-12-1997	AU 3294197 A	05-01-1998
		CA 2252754 A	11-12-1997
		CN 1221500 A	30-06-1999
		EP 0902919 A	24-03-1999
		US 5920483 A	06-07-1999
		US 5903459 A	11-05-1999
EP 0519638 A	23-12-1992	DE 69212786 D	19-09-1996
		DE 69212786 T	19-12-1996
		DE 69223457 D	22-01-1998
		DE 69223457 T	02-04-1998
		EP 0548301 A	30-06-1993
		ES 2090650 T	16-10-1996
		WO 9222785 A	23-12-1992
		JP 5272903 A	22-10-1993
		JP 6500740 T	27-01-1994
		US 5257460 A	02-11-1993
		US 5478300 A	26-12-1995
US 4547847 A	15-10-1985	US 4509126 A	02-04-1985
		IT 1176155 B	18-08-1987
		CA 1208050 A	22-07-1986
		CA 1218883 C	10-03-1987
		DE 3348159 C	17-12-1992
		DE 3390033 C	22-06-1989
		DE 3390033 T	14-06-1984
		GB 2133187 A,B	18-07-1984
		GB 2168828 A,B	25-06-1986
		WO 8304445 A	22-12-1983
EP 0740982 A	06-11-1996	JP 9011167 A	14-01-1997
US 4782598 A	08-11-1988	US 4663852 A	12-05-1987
US 4939678 A	03-07-1990	US 4884889 A	05-12-1989
		AT 99410 T	15-01-1994
		DE 3886767 D	10-02-1994
		DE 3886767 T	11-05-1994

Form PCT/ISA/210 (patent family annex) (July 1992)

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/US 99/18968

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 4939678 A		EP 0386115 A	12-09-1990
		JP 2694986 B	24-12-1997
		JP 3501052 T	07-03-1991
		WO 8904945 A	01-06-1989

Form PCT/ISA/210 (patent family annex) (July 1992)